# Challenges of Human-Robot Communication In Telerobotics

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**Abstract** - *Some general considerations are presented on bilateral human-telerobot control and information communication issues. Advances are reviewed related to the more conventional human-telerobot communication techniques, and some unconventional but promising communication methods are briefly discussed. Future needs and emerging application domains are briefly indicated.*

## 1. INTRODUCTION

Remotely operated robots or, in today's taxonomy, "telerobots" typically perform non-repetitive or singular work under a variety of environmental conditions ranging from structured to unstructured conditions. Telerobot control is characterized by a direct involvement of the human operator in the control since, by definition of task requirements, teleoperator systems extend or augment human manipulative, perceptual and cognitive skills. This capability is far beyond what is obtainable with today's industrial robots. As a consequence, the human operator interface to or two-way communication with a telerobot becomes a critical issue.

Continuous human operator control in teleoperation has both advantages and disadvantages. The main advantage is that overall task control can rely on human perception, judgment, decision, dexterity and training. The main disadvantage is that the human operator must cope with a sense of remoteness, be alert to and integrate many information and control variables, and coordinate the control of one or two mechanical arms each having many (typically six) degrees of freedom - and doing all these with limited human resources. Furthermore, in many cases like space and deep sea applications, communication time delay interferes with continuous human operator control.

Modern development trends in telerobot control technology are aimed at amplifying the advantages and alleviating the disadvantages of the human element in control by the development and use of advanced sensing, graphics displays, intelligent computer controls, and new computer-based man-machine interface devices and techniques in the information and control channels.

Automation in teleoperation is distinguished from other forms of automated systems by the explicit and active participation of the human operator in system control and information management. Such active participation by the human, interacting with automated system elements in teleoperation is characterized by several levels of control and communication, and can be conceptualized under the notion of "supervisory control" [1]. The man-machine interaction levels in teleoperator control and communication can be considered in a hierarchical arrangement as outlined in [2]:(i) planning or high level algorithmic functions, (ii) motor or actuator control functions, and (iii) environmental interaction sensing functions. These functions take place in a task context in which the level of system automation is determined by (a) the mechanical and sensing capabilities of the telerobot system, (b) real time sensing, (c) the amount, format, content and mode of operator interaction with the telerobot system, (d) environmental constraints, like task complexity and (e) overall system constraints, like operator's skill or maturity of machine intelligence techniques.

In the second section of the paper some general considerations are presented on control and information issues in telerobotics. In the paper's third section advances are reviewed related to the more conventional human-robot (h/r) communication techniques. The fourth section of the paper is devoted to a brief discussion of some unconventional but promising h/r communication modes. The paper concludes with some note on future needs and direction in the development of h/r communication modalities in telerobotics.

## 2. GENERAL CONSIDERATIONS

Task level control of robot arms requires the coordinated motion and/or force control of several (typically six) robot arm joints while observing a variety of kinematic, dynamic and environmental constraints. Then, to comply with the specifics of a given tack, different sensor signals must be interpreted in real time. Furthermore, manipulation tasks can often be performed in different ways. Hence, robot arm task-level control implies a multilevel decision and monitoring process at both the control input and information feedback channels.

It is know that the human operator's input and output channel capacities are not only limited but also asymmetric; the human has much more information receiving (input) channels than information conveying (output) channels. In this sense, the human operator represents a limiting factor in the complex information and control environment of a remotely operated robot. Following this recognition, the general objectives of control, information and man-machine interface development for telerobots as man-extension systems are: Provide devices and techniques which enable the human operator to convey control commands to and receive control feedback from the remotely operated robot in comprehensive, integrated and task-level terms and formats. This can be accomplished by the use of data driven automation.

Data driven automation here refers to the use of models and sensing sources through computers in the control of remotely operated robots. Data derived from models typically provide apriori information about robot machines and tasks. Data derived from sensing sources typically provide on-line information about robot task performance. Data driven automation is inherently flexible since it is programmable. It contrasts the mechanically fixtured, rigid or fixed automation.

Application of telerobots as man-extension systems requires flexibility in both control and information management in order to cope efficiently with varying and unpredictable task conditions. The use of data driven automation offers significant new possibilities to enhance overall task performance by providing programmable devices and techniques for task-level ("intelligent") controls and displays.

## 3. ADVANCES IN CONVENTIONAL TECHNIQUES

The conventional h/r communication techniques consist of manual (continuous or analog) control, keyboard-type (discrete or symbolic) control, visual displays like TV camera monitors and displays including some computer graphics ("virtual reality") techniques. Advances in these more conventional techniques are illustrated by examples developed by the Advanced Teleoperator (ATOP) project at the Jet Propulsion Laboratory (JPL) during the past fifteen or so years.

### 3.1 Manual Controls

The human arm and hand are functionally both powerful mechanical tools and delicate sensory organs through which information is received from and transmitted to the world. Therefore, the human arm-hand system (thereafter simply called hand here) is a key communication medium in teleoperator control. With hand actions, complex position, rate, or force commands can be formulated and very physically written to the controller of a remote robot arm system in all workspace directions. At the same time, the human hand also can receive force, torque, and touch information from the remote robot arm-hand system. Furthermore, the human fingers offer additional capabilities to convey new commands to a remote robot controller from suitable hand controllers. Hand controller technology is, therefore, an important technology in the development of advanced teleoperation. Its importance is particularly underlined when one considers computer control which connects the hand controller to the remote arm system. The direct and continuous (scaled or unscaled) relation of operator hand motion to the remote robot arm's motion behavior in real time through a hand controller is a sharp contrast to the computer keyboard type commands which, by their very nature, are symbolic, abstract, and discrete (noncontinuous), and require the specification of some set of parameters within the context of a desired motion.

In contrast to the standard force-reflecting master-slave systems, a new form of bilateral, force-reflecting manual control of remote robot arms has been implemented at JPL. It utilizes a general purpose force-reflecting hand controller (FRHC) [3]. The hand controller is a six-degree-of-freedom control input device that can be back-driven by forces and torques sensed at the base of the end effector of a remote robot arm. This hand controller is general purpose in the sense that it does not have any geometric and dynamic similarity to the slave arm it controls; it is not a replica of any slave arm, but it can be coupled to and used for the control of any remote slave arm through appropriate mathematical transformations implemented in a computer control system. It is also suited for interactive telerobot control.

Interactive remote manipulator control signifies here a hybrid manual and automatic control capability which allows that some motions of the remote robot arm in work space coordinates are under manual control while the remaining motions in the same work space reference frame are under automatic computer control based on sensor information originating from the robot end effector. It is noted that, in this hybrid control system, the manual control is in task-level terms which also requires a computer in the control system. The sensor-referenced automatic controls are also in task-level terms defined within a pre-programmed control menu. In this control mode, the operator and automation share the control.

The computer-based control system of the FRHC supports four modes of manual control: position, rate, force-reflecting, and compliant control in task space (Cartesian space) coordinates. The operator, through an on-screen menu, can designate the control mode for each task space axis independently. The *position control mode* servos the slave position and orientation to match the master's. The *indexing function* allows slave excursions larger or smaller than the 30-cm cube hand controller work volume. In the *force-reflecting mode*, the hand controller in backdriven based on force-moment data generated by the robot and sensed during the robot hand's interaction with objects and environment. The *rate control mode* sets the slave endpoint velocity in task space based on the displacement of the hand controller. This is implemented through a software spring in the control computer of the hand controller. Through this software spring, the operator has a sensation of the commanded rate, and the software spring also provides a zero-referenced restoring force. The rate mode is useful for tasks requiring large translations. The *compliant control mode* is implemented through a low-pass software filter acting on the robot hand's force-torque sensor data in the hybrid position-force loop. This permits the operator to control a springy or less stiff robot. Active compliance with damping can be varied by changing the filter parameters in the software menu. Setting spring parameter to zero in the low-pass filter will reduce it to a pure damper which results in a high stiffness hybrid position-force control loop.

The original FRHC has a simple hand grip equipped with a deadman switch and with three function switches. To better utilize the operator's finger input capabilities, an exploratory project evaluated a design concept that would place computer keyboard features attached to the hand grip of the FRHC. To accomplish this, three DATAHAND™ [4] switch modules were integrated with the hand grip. Each switch module at a finger tip contains five switches. Thus, the three switch modules at the FRHC hand grip can contain fifteen function keys which can directly communicate with a computer terminal. This eliminates the need for the operator to move his/her hand from the FRHC hand grip to a separate keyboard to input messages and commands to the computer. A test and evaluation, using a mock-up system and ten test subjects, indicated the viability of the finger-tip switch modules as part of a new hand grip unit for the FRHC as a practical step towards a more integrated operator interface device [5]. More on the FRHC and on hand controller technology in general can be found in [6].

### 3.2 Computer Keyboard Controls

Human-robot control communication through computer keyboard controls assumes the availability of some preprogrammed or on-line programmable control menu. A control menu renders h/r control communication indirect and places it on an abstract computer "language" level. A telerobot control menu can be a very simple one or it can be a very sophisticated one by using some grammar and implying some task context.

While manual controls have a more or less intuitive "body" appeal to an operator and require relatively simple training procedures, computer keyboard controls of telerobots have an intense appeal to the human cognitive skill and require some specific schooling in computer programming.

An important note is in place here: one has to distinguish or separate the so called "front end" or "user end" computer keyboard controls from the keyboard controls available to control program developers. While control program developers are bound to be interested in exploiting specific features and capabilities of an operating system and programming language to construct a useful telerobot control program, the "end user" (the actual operator) is more interested in dealing with a simple "front end" architecture of computer keyboard controls to perform actual telerobotic tasks. As of yet, there are no maintainable standards for "front end" architecture of computer keyboard control communication in telerobotics. Each existing system has its own standard that is understandable mostly to the actual system developers. NASREM [7] only represented an unfinished initiative to define a common standard, and was basically focused at the background architecture of a general "user's front end" keyboard control.

### 3.3 Visual Displays

Task visualization is a key problem in telerobotics, because most of the operator's control decisions are based on visual or visually conveyed information. The key visual information originates from TV cameras. An auxiliary source of visual information is computer graphics which plays an increasingly important role in telerobotic systems.

**3.3.1 TV Camera Displays** - The actual challenges to acquire and display TV camera information go far beyond the scope[1] for an optimized conventional static arrangement of TV camera and monitor control. The challenges are focused at issues of acquiring and conveying *stereo* vision information and of connecting all this activity to the head/eye motion of an operator (*head-mounted displays*) in order to create a proper visual environment for telepresence (or tele-existence); see details in [8 and 9].

It is noted that head-mounted or helmet-mounted display is only one method to create geometrically correct visual telepresence. Other methods are described in [10 and 11], using "virtual window" technique based on a fixed high-resolution stereo video system with head tracking, corresponding camera positioning, and image reproduction to each eye to correspond to what the viewer would see were he/she looking through a fixed window.

It has yet to be shown, as pointed out in [1], how important is the sense of "feeling present" per se as compared to simply having high resolution, a wide field of view, and other attributes of good visual sensory feedback. It is noted that [12] describes a high-resolution, wide view angle head-mounted display using eye movement tracking, with favorable experimental results.

**3.3.2 Computer Graphics Displays** - The role of computer graphics in telerobotics includes 1) planning actions, 2) previewing motions, 3) predicting motions in real time under communication time delay, 4) helping operator training, 5) enabling visual perception of nonvisible events like forces and moments, and 6) serving as a flexible operator interface to the computerized control system.

The capability of task planning aided by computer graphics offers flexibility, visual quality, and a quantitative design base to the planning process. The capability of graphically previewing motions enhances the quality of teleoperation by reducing trial-and-error strategies in the hardware control and by increasing the operator's confidence in control decision making during task execution. Predicting consequences of motion commands in real time under communication time delay permits longer action segmentations as opposed to the move-and-wait control strategy normally employed when no predictive display is available, increases operation safety, and reduces total operation time. Operator training through a computer graphics display system is a convenient tool for familiarizing the operator with the teleoperated system without turning the hardware system on. Visualization of nonvisible effects (like contact forces) enables visual perception of different nonvisual sensory data, and helps manage system redundancy by providing some suitable geometric image of a multidimensional system state. Last, but not least, computer graphics as a flexible operator interface to the control systems; it replaces complex switchboard and analog display hardware in a control station.

The actual utility of computer graphics in teleoperation depends to a high degree on the fidelity of graphics models that represent the teleoperated system, the task, and the task environment. The JPL ATOP project developed a method for high-fidelity calibration of graphics images to actual TV images of task scenes. This development has four major ingredients: first, the creation of high-fidelity three-dimensional graphics models of robot arms and objects of interest for robot arm tasks; second, the high-fidelity calibration of the three-dimensional graphics models relative to given TV camera two-dimensional image frames which cover the sight of both the robot arm and the objects of interest; third, the high-fidelity overlay of the calibrated graphics model over the actual robot arm and object images in a given TV camera image frame on a monitor screen; fourth, the high-fidelity motion control of robot arm graphics image by using the same control software that drives the real robot.

The high-fidelity fused virtual and actual reality image displays became very useful tools for planning, previewing, and predicting robot arm motions without commanding and moving the robot hardware. The operator can generate visual graphics image superimposed over TV pictures of the live scene. Thus, the operator can see the consequences of motion commands in real time, before sending the commands to the remotely located robot. The calibrated virtual reality display system can also provide high-fidelity synthetic artificial TV camera views to the operator. These synthetic views can make critical motion events visible that are otherwise hidden from the operator in a given TV camera view or for which no TV camera view is available.

The current calibration method uses a point-to-point mapping procedure, and the computation of camera parameters is based on the ideal pinhole model of image formation by the camera. In the camera calibration procedure, the operator first enters the correspondence information between the three-dimensional graphics model points and the two-dimensional camera image points of the robot arm to the computer. This is performed by repeatedly clicking with a mouse a graphics model point and it corresponding TV image point for each corresponding pair of points on a monitor screen which, in a four-quadrant window arrangement, shows both the graphics model and the actual TV camera image. To improve calibration accuracy, several poses of the manipulator within the same TV camera view can be used to enter corresponding graphics model and TV image points to the computer. Then the computer computes the camera calibration parameters. Because of the ideal pinhole model assumption, the computed output is a single linear $4 \times 3$ calibration matrix for a linear perspective projection.

The actual camera calibration and object localization computations are carried out by a combination of linear and nonlinear least-squares algorithms. The linear algorithm, in general, does not guarantee the orthonormality of the rotation matrix, providing only an approximate solution. The nonlinear algorithm provides the least-squares solution that satisfies the orthonormality of the rotation matrix, but requires a good initial guess for a convergent solution without entering into a very time-consuming random search. When a reasonable approximate solution is known, one can start with the nonlinear algorithm directly. When an approximate solution is not known, the linear algorithm can be used to find one, and then one can proceed with the nonlinear algorithm. More on the graphics system in the ATOP control station and on the graphics calibration and its transcontinental demonstration can be found in [13 - 20].

Graphics displays are also useful for displaying non-visual sensor information. Graphics displays of proximity, touch, slip, and force-torque sensor information transform non-visible or hardly-visible events into visually perceivable forms on a graphic terminal. Graphics displays of sensor information can be used in both manual and computer control modes. In a manual control mode the displays are elements in the continuum of a real-time control loop in the sense that they guide the operator's continuous control input by providing continuous information feedback on the appropriate "external error state" of the robot hand. In a computer control mode, the displays represent discrete elements outside the real-time control loop. They provide information to the operator prior to the selection and initialization of an appropriate sensor-referenced computer control algorithm, and inform the operator about the performance of the control algorithm selected for the task at hand.

The stream of data generated by sensors on a "smart hand" (proximity, touch and force-torque sensors) provides multidimensional information, and requires quick (sometimes split-second) control response. In general, the control decision required to respond to the data is also multidimensional. This represents a demanding task and heavy workload for the human operator. It is also recognized that the use of information from sensors on a "smart hand" often require coordination with visual information. *Event Driven Displays* can mitigate this problem. These displays can concisely encode the information content of multidimensional sensor data and thereby aid the operator's perceptive and decision making task [2].

By definition, event-driven displays map a control goal or a set of subgoals into a multi-dimensional data space based on the fact that control goals or subgoals always can be expressed as a fixed combination of multidimensional sensory data. Event-driven displays can be implemented by real-time computer algorithms which (i) coordinate and evaluate the sensory data in terms of predefined events and (ii) drive the graphics display. Flexible display algorithms require a variable set of task oriented parameters specifiable by the operator in order to match the specific needs of a given control task.

Moreover, *Event Controlled Displays* can extend the capabilities of event-driven displays by automatically effecting changes between data displays and data formats on a graphics monitor. The need for different types of sensor data displays or for different formats of data displays typically arises in a logical sequence in remote robot control tasks. For example, when proximity sensor data are needed then normally there is no need for touch or force-torque sensor data, or vice versa. This sequential logic in the need of sensor information can be utilized to switch automatically between different data displays or formats. Following this concept, event-controlled displays have been implemented at JPL [22]. In the implemented examples predefined changes in sensor data automatically effect changes in display modes, formats and parameters, matching the need for a particular information to different phases of the task. Event-controlled displays required the implementation of state transition nets in real-time computer programs base don event detection logic.

Event controlled or automatic display mode/format switching can alleviate much of the display control workload for the operator. More on Event Driven and Event Controlled Displays can be found in [21, 22].

Graphics displays are also useful for creating "virtual sensors." The notion of "virtual sensors" is referred to the simulation of sensors in a computer graphics environment that relate the simulated telerobot's interaction with simulated objects. Examples are quoted in [15 and 23]. Note that an accurate simulation of contact forces/moments can be very computation intensive, but approximate simulations can be accomplished without major difficulties.

## 4. UNCONVENTIONAL TECHNIQUES

The use of voice and the use of eyegaze offer two new unconventional communication channels to control machines.

### 4.1 Voice Communication

Note that the human audio/vocal communication channel does not require manual or some specific visual contact between operator and machine, and it is essentially omnidirectional and always open.

Advancements in computer-based voice recognition systems make the direct use of human speech feasible for control applications in a teleoperator control station. Several such application have been developed at JPL [24]. A specific application system was developed for the control of the Space Shuttle TV cameras and monitors while the operator manually controls the Shuttle robot arm. In this application the operators could "push" control switches by voice instead of using fingers. Some Shuttle robot arm tasks are visually very demanding, and can require 50 to 70 commands to four TV cameras and two TV monitors within 15-20 minutes time frame to assure sufficient visual feedback to the operator. The ground control tests at the Johnson Space Center [25] have shown 96 to 100% voice recognition accuracy for the' best test runs and resulted in the following major conclusions: (i) the application concept is realistic and acceptable; (ii) the use of voice commands indeed contributes to a better man-machine interface integration; (iii) individual human acoustic characteristics and training have a major impact on system performance.

Several alternative combinations of control vocabulary words with and without syntax restrictions were developed and tested. Altogether thirty-six control switches had to be activated by voice commands. The training experiments have shown that the operators prefer simple vocabularies with minimum or no syntactic restrictions. To cope with this devocabularies were constructed using concatenated words for full action commands. As it turned out, the operators remembered and used with higher confidence buzzword-like voice commands than words which were embedded into syntactic procedures.

### 4.2 Eyegaze Communication

The Eyegaze System [26] is basically a tool for measuring, recording, playing back, and analyzing what a person is doing with his eyes. The system uses the Pupil-Center/Corneal-Reflection method to determine the eye's gaze direction. A video camera located below the computer screen, or below the' work space when computer monitor is not used, continually observes the subject's eye. A small, low-power infrared light emitting diode (LED) located at the center of the camera lens illuminates the eye. The LED generates the corneal reflection and causes the bright pupil effect which enhances the camera's image of the pupil. Specialized image processing software identifies and locates the centers of both the pupil and corneal reflection. Trigonometric calculations then project the subject's gaze point based on the position of the pupil center and corneal reflection within the video image. No attachments to the head are required.

The Eyegaze System [?7] allows people with physical disabilities to operate a computer with their eyes. By looking at graphically displayed control keys on a computer monitor, a person can control the environment (lights, appliances, TV, etc.), type, operate a telephone, and run computer software, etc. These systems are used around the U. S., Canada and Europe by children and adults, Its use requires: (i) good control of one eye, (ii) the ability to keep the head still in front of the Eyegaze Camera, (iii) a brief, 15-second calibration procedure, and (iv) a fluorescent rather that incandescent room lighting.

It would be interesting to try out the quoted Eyegaze System for some control operations in a telerobotic control station.

## 5. CONCLUSIONS

Some advances have been made in telerobotics technology through the introduction of various sensors, computers, automation and new man-machine interface devices and techniques for remote manipulator control. The development of dexterous mechanisms, smart sensors, flexible computer controls, intelligent man-machine interfaces, and innovative System designs for advanced teleoperation is, however, far from complete, and poses many interdisciplinary challenges. It should also be recognized that the normal manual dexterity of humans is more a "body" skill than an intellectual one. The man-machine interface philosophy embodied in the force-reflecting master-Slave' manipulator Control" technology has been founded mainly on this fact. Advanced teleoperation employing sensor-referenced and computer-controlled manipulators shifts the operator-telerobot interface from the body (analog) level to a more intellectual language-like (symbolic) level. Research efforts for developing new man-machine interface technology for advanced teleoperation will have to render the ]a],:,Lla:,c-like symbolic interface between human operator and telerobot as efficient as the conventional analog interface. This remark also applies to operator interface development for procedure execution aids and for expert systems in teleoperator action planning and error recovery [28].

The application domain of telerobotic technologies is expanding as exemplified, e.g., by the emerging fields of telemedicine, telesurgery, telescience, etc. The issues and challenges in human-robot communication in the emerging application domains will attain new dimensions and increased importance.

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